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Influence of clamping systems during milling of carbon fiber reinforced composites

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Abstract

Carbon fiber reinforced composites (CFRP) are mostly manufactured near net shape. Nevertheless, a final milling step at the edges of the cured components is still necessary. Damages which occur during milling or drilling of CFRP lower the durability of the components and increase the production costs. Requirements concerning the clamping system for milling or drilling CFRP are rising simultaneously with increasing complexity of the components. This stresses the need for complex clamping systems like linear clamping jaws around the whole workpiece. However such types of clamping systems induce poor accessibility to the component being worked on and hence longer machining time. As a result to the need for complex clamping systems, the production costs are increased. Therefore, several benefits can be achieved by increasing the distances between the clamping points of the clamping system to reduce machining time and production costs. This paper discusses investigations of milling tests with variable clamping conditions of the workpieces. In the experiments a linear milling operation the edge of the workpiece is examined. The clamping of the planar specimens was realized with a clamping system which enables the adjustment of different distances between the clamping points of the specimen. The process forces and the resulting damage at the workpiece surfaces were measured during the experiments. These results are compared with a linear clamping system to examine the influence of rising clamping distances. The results demonstrate that the distance of the clamping points while milling the edge of the workpiece has a significant influence on the process forces.

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1. Introduction

The range of applications for carbon fiber reinforced plastics (CFRP) has increased continuously in the last few years. Due to the challenge to create lightweight products to save natural resources, this material has become more established in major industries such as the automotive industry. A high design freedom based on the production process for manufacturing CFRP workpieces allows the creation of novel lightweight products. Additionally CFRP have a high specific strength and stiffness. Workpieces made of continuous carbon fibers are usually built up with a specific ply stack with different fiber orientation for each ply. Within every ply the fibers are orientated longitudinally inside the workpiece [1]. The CFRP workpieces are mostly manufactured near net shape due to the manufacturing process. Nevertheless, post processing is necessary. Most common processes include drilling boreholes and milling the edges of the workpiece. During machining, different types of damage may occur which were already described a few years

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ago [2-5]. The most common type of damage is called delamination. This type of damage leads to a separation of the different plies. At the upper side of the workpiece the damage is called ‘peel-up’ delamination and at the lower side it is called ‘push-out’ delamination [6]. To avoid damaging the workpiece the machining process as well as the clamping system of the workpiece need to be adapted to the workpiece material and geometry. A further advantage of fiber reinforced composites (FRP) is the ability to design complex geometries. However, complex geometries also require complex clamping systems for drilling and milling processes to ensure the accuracy of the machining [7]. With increasing complexity of the workpiece, the demands for the clamping systems to ensure the processability are also increasing. Most clamping devices for machining complex shaped FRP workpieces work with pneumatic (vacuum) or mechanic clamping devices. Pneumatic clamping devices are mostly inflexible to changes of the workpiece geometry. Therefore these types of clamping systems are really cost intensive and can only be used for one type of workpiece. Consequently, the use and complexity of CFRP can be encouraged by developing adapted mechanic clamping systems [8].

In the past, little research work was made regarding clamping systems for FRP. To reduce the delamination at the entry side of the drill tool, Sadat developed a pressure device which supports the upper surface layer against delamination. To protect the exit side of the workpiece an aluminum backup plate was used [9]. The behavior of thin composite laminates while drilling a supported and unsupported borehole has been investigated by Capelleo. Within this investigation the unsupported drilling shows divergent progression of the cutting torque and the thrust force [10]. Tsao and Hocheng developed a mechanical model to determine the accruing delamination with and without a backup plate for different drill types. The results show that the core drill and the candle stick drill allow for the highest feed rate without any delamination while the twist drill shows the worst feed rate [11]. Kaufeld et al. investigated the influence of the length of a cantilever beam during drilling with regard to the induced damage. It was assessed that the increasing length of the cantilever beam leads to a slight decrease of the axial forces of the drill tool. Additionally, the damage of the upper surface increases rapidly when reaching a critical limit [12]. The influence of different clamping systems on the achievable workpiece quality has been investigated for drilling operations. The results show that the resulting workpiece quality depends heavily on the clamping system and the position of the clamping points [7, 8]. The influence of clamping systems during the milling of FRP has not been investigated fundamentally yet.

2. Experiments

2.1. Experimental setup and scope

To investigate the influence of the clamping system on the resulting workpiece quality, a specific clamping system was developed, see Fig. 1. This system allows the detection of the influence of different distances between fixation lines which are compared with a nearly ideal clamping system. The experimental device is shown in Fig. 1. Within the planar clamping device the material is fixed across the whole cutting length and therefore no deflection of the workpiece is possible, see Fig. 2 a. This clamping arrangement can be interpreted as an ideal clamping system. Hence during this test the stiffness of the workpiece is infinite. On the other hand, at the linear clamping device the workpiece is only fixed on the left and right side, see Fig. 2 b. Between the clamping lines there is no support of the lower and the upper side of the workpiece. Therefore at the linear clamping device the deflection and the vibration behavior during milling could be detected.

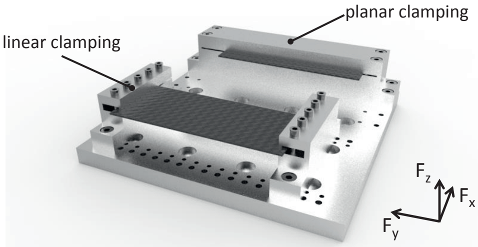

Fig.1. Variation of the clamping system and an ideal clamping system

During the milling tests the length l_x of the workpiece varied from 105 to 225 mm. The variation of the distance of the clamping system was realized with a device which can be adjusted along the direction $l_{y,l}$, see Fig. 2 b. The length of the workpiece at the planar clamping tests $l_{y,p}$ was chosen to be equal to the length of the linear clamping tests $l_{y,l}$. The variation of the distance of the clamping system could be adjusted in steps of 15 mm. Therefore between 105 mm and 225 mm 9 tests were carried out. Every test was repeated four times for statistical verification. The screws of the clamping device were fixed with a torque of 12 Nm. To determine the influence of the clamping system, the procedure was made similar to the drilling tests which were made with a 4-point clamping system [8].

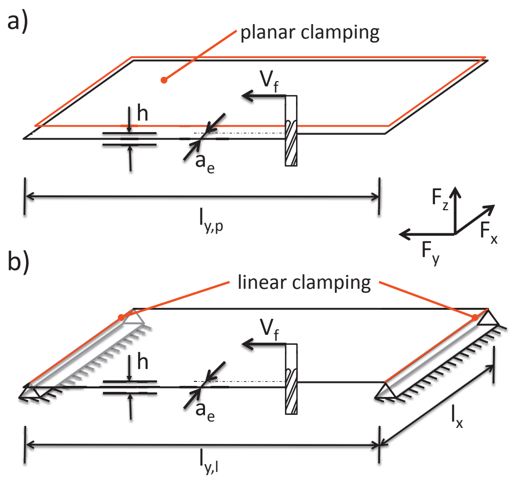

Fig.2. a) planar clamping system, b) Variation of the distance between the clamping lines

The forces determined at the planar clamping tests show the influence of the milling process. The comparison of the forces of the linear clamping tests and the planar clamping tests show the influence brought by the clamping system. All experiments were carried out using a machining center from Heller type MC-16. During the tests the forces F_x, F_y and F_z were measured with a multicomponent force plate Kistler 9255. It is expected that the deflection increases with increasing distance of the linear clamping system. During this test, only the measurement of the process force could be made. The measurement of the deflection will be part of future milling tests.

2.2. Material data and process parameter

The used sample material in these experiments is a carbon fiber composite based on an epoxy matrix. Within these tests the same material was used which is identical to the test for investigating the influence of clamping systems during drilling CFRP [8]. The type of the fibers is T620SC 24 K 50C produced by the Toray company. The material consists of eight plies with biaxial textiles. The fiber orientation was quasi-isotropic (0°/90° and +45°/-45°). The stack up and the epoxy matrix flat plates were pressed with the resin transfer molding process. The plates have dimensions of 860 mm x 510 mm x 2.5 mm. The sample material was cut out of thin plates. The dimensions of the sample material depend on the distance of clamping device which is used. The width l_x was tested with values, 40 mm and 80 mm. Young's modulus of the composite is 46100 MPa.

The milling tool which was used in this experiment was made of cemented carbide. The milling tool was designed according to DIN 6527 L.

Table 1. Parameters of the milling tool used in the experiment.

Parameter	Milling tool
Diameter	6 mm
Number of cutting edges	2
Helix angle	30°

Before the main tests were realized, preliminary investigations were made to find appropriate parameters. The parameters were set as a result of these preliminary milling tests. The speed of the milling tool was determined at 4775 rpm which yields a cutting speed of $v_c = 90$ m/min. The feed velocity was fixed at 1433 mm/min which yields a feed rate per tooth of $f_z = 0{,}15$ mm. The contact width was held constant throughout the tests. The contact width was fixed at $a_e = 3$ mm.

2.3. Measurement of the cutting forces

During the milling tests the cutting force was recorded in the x-, y- and z-direction. After the milling tests, the recorded forces were analyzed with regard to the difference between the ideal clamping system and the influence of the clamping system at different clamping distances. During the measurement, a sampling rate of 20 kHz was attuned. Therefore, the cutting width a_e and the diameter of the milling tool yield an angle ϕ of 90°, see Fig. 3.

In Fig.3 it can be seen that the cutting forces are not expected to be constant. It is noted that the cut interrupts two times during one revolution of the milling tool. Therefore the excitation frequency is two times higher than the speed of the milling tool. This should be taken into consideration when evaluating the cutting forces during edge milling.

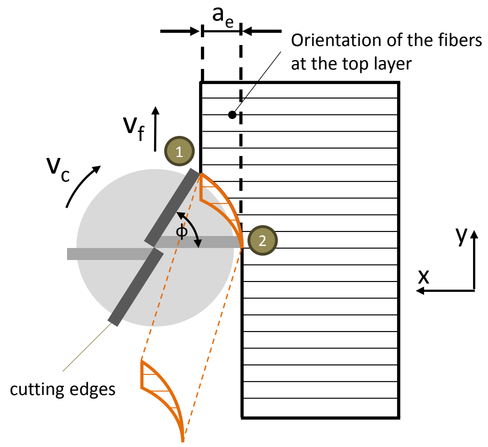

Fig.3. Cutting conditions during milling the edges, 1) describes the entry of the cutting edge, 2) describes the exit of the cutting edge

Given the angle ϕ, the speed of the milling tool and the sampling rate it can be calculated how many measurements were made during the cut of one chip. It is thus obtained that within the cutting process of one chip, 63 measurements of the cutting forces were made.

3. Results

3.1. Cutting forces

During the milling tests the cutting force was measured. In figure 4 the cutting force for a planar clamping system is shown exemplarily. In x-direction the biggest cutting forces of approximately 120N could be measured. In all directions the forces remain constant during the whole milling of the edge. That implies that no deflection and vibration of the specimen occurred during the cut. The progression during the milling of an edge in a linear clamping device with a distance of $l_{y,l} = 225$ mm is shown in Fig.6. The progression of the curves in x- and y-direction is almost similar to the force progression of the planar clamping system. The value of the forces in the y-direction is 20-30 N higher at the linear clamping system compared to the planar clamping system. The progression of the z-force is different than the one of the planar clamping test.

At the beginning of the milling near the clamping line the force is similar to the planar clamping system. With rising distance relative to the clamping line, the force is getting higher. The largest force of 150 N was measured at the middle of the workpiece. Afterwards the force is decreasing again until it reaches the second clamping line and obtaining a force which is similar to the planar clamping system.

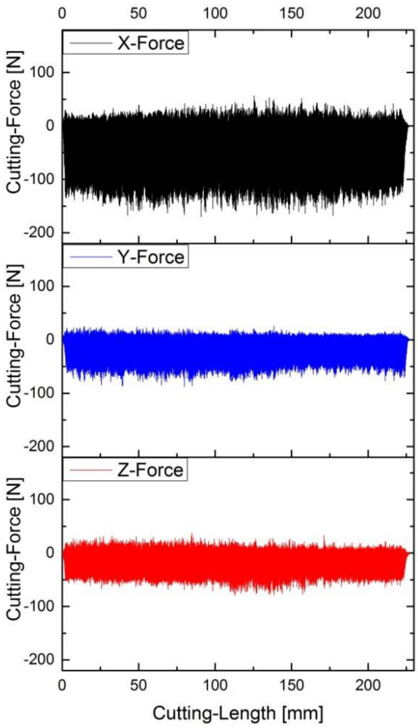

Fig.4. Cutting forces during milling an edge in a planar clamping device ($l_{y,p}$ = 225 mm)

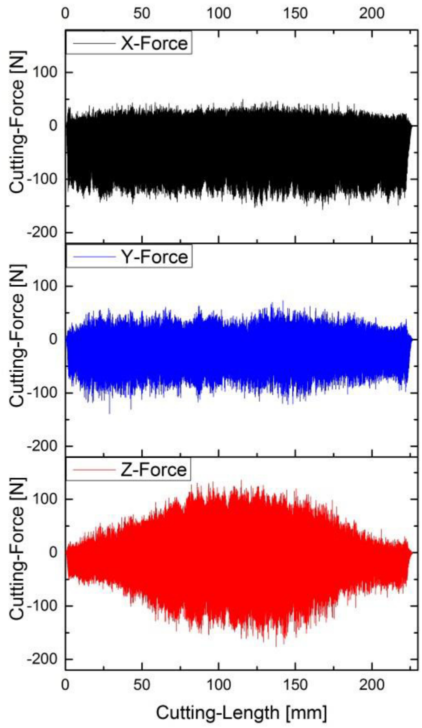

Fig.6. Cutting forces during milling an edge with the length l_y with a linear clamping device ($l_{y,l}$ = 225 mm, l_x = 80 mm)

3.2. Workpiece quality

During the entire milling test the quality of the workpieces was recorded. The detected delamination was negligible and even smaller than the measurement inaccuracy, see Fig5. Therefore it can be established that the variation of the distance between the clamping lines has no influence on the workpiece quality for this material in particular. This behavior is only valid for clamping distances up to $l_{y,l}$ = 225 mm, see Fig.5 b. For higher distances the formation of damage might be possible.

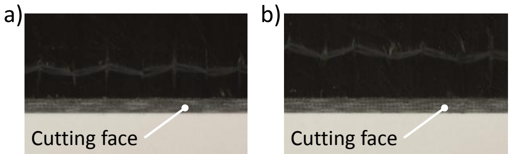

Fig.5. Cutting face of the workpiece, a) for planar clamping; b) for linear clamping at the middle of the cutting length $l_{y,l}$ = 225 mm

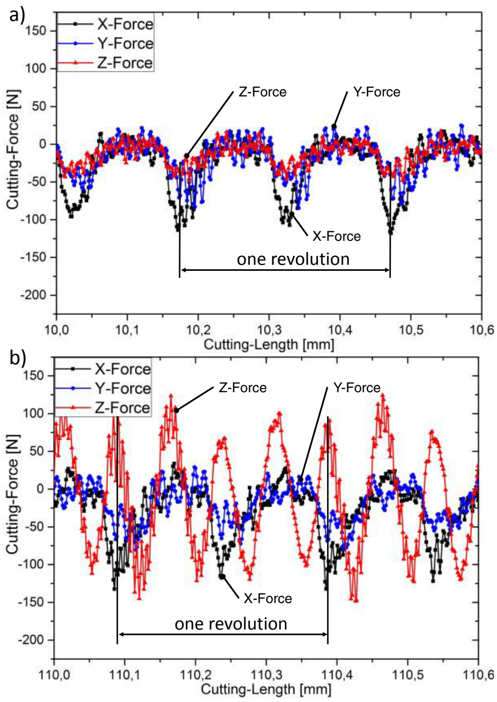

Fig.7. Section of the cutting forces during milling an edge with a linear clamping device ($l_{y,l}$ = 225 mm, l_x = 80 mm) a) after the entry of the milling tool, b) in the middle between the two clamping lines.

4. Discussion

The shift of the progression of the cutting forces during a cut in an linear clamping system with the length $l_{y,l}$ = 225 mm is shown in figure 7. At the entry of the milling tool the frequency of the cutting forces can be linked to the cutting process, see Fig.7 a. During one revolution two cuts were made. These two cuts are visible in the force progression while the z-force is oscillating between 0 N and -50 N. In the middle of the workpiece the force progression, especially the progression of the z-force changed significantly and shows a different behavior in comparison to the entry of the milling tool, see Fig.7 b. Obviously the frequency of the z-force is nearly doubled. Furthermore the magnitude of the z-force has been also increased sharply. The force progression of the x- and y-force seems to be unaffected by the clamping system.

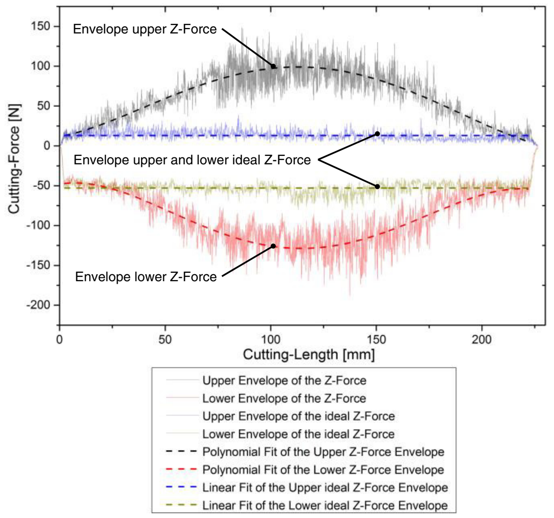

Fig.8. Cutting forces during milling an edge with the length ly with a linear clamping device ($l_{y,l}$ = 225 mm, l_x = 80 mm)

To assess the cutting force resulted from the planar and linear milling tests with a certain cutting length, the z-forces were delineated into a diagram, see Fig.8. The depiction of the whole force measurement makes it difficult to recognize the differences of the clamping systems caused by the numerous measure points. Therefore to improve the visualization of the results only the upper and the lower envelope of the cutting forces is depicted into Fig.8. The upper and lower envelope for the planar clamping tests remains constant during all milling tests. Therefore these forces can be approximated by a constant. The forces of the linear clamping system show, at the beginning and the end of the milling test, a good alignment with the planar milling test.

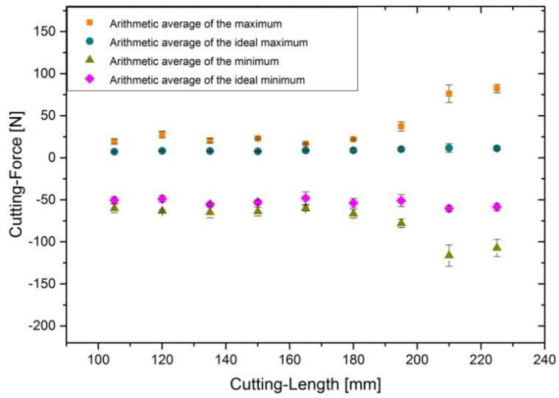

Fig.9. Comparison of the maximum and minimum cutting forces in z-direction of the linear and the planar clamping system during milling an edge depending on the length l_y (l_x = 40 mm)

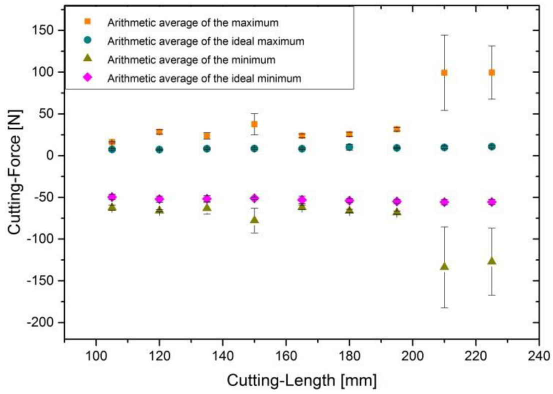

Fig.10. Comparison of the maximum and minimum cutting forces in z-direction of the linear and the planar clamping system during milling an edge depending on the length l_y (l_x = 80 mm)

With rising distance of the milling tool from the clamping line the magnitude of the z-force rises continuously till the force reaches the maximum turning point at the middle of the workpiece. As also shown in Figs. 6 and 7, strong vibrations can be observed. In the middle of the workpiece the magnitude is approximately 100 N higher than the force at the planar clamping system. The progression of the maximum and minimum cutting force in z-direction was approximated by a function of fourth order, see Fig.8.

The arithmetic averages of the maximum and minimum forces are shown for the lengths l_x = 40 mm (see Fig. 9) and l_x = 80 mm (see Fig. 10). For the length l_x = 40 mm the comparison between the highest amplitude of the planar and the linear clamping system is shown, see Fig.9. The arithmetic average was calculated from the four repetitions of every milling test. The distribution of the values which were measured during the tests is quite small. This is confirmed by the standard deviation of the single measurement. Within the tests the same material behavior could be established, independent of the length l_x. With increasing distance between the clamping lines the amplitudes remain constant till the length $l_{y,l}$ reaches a critical level. At this level, which is roughly located at the clamping distance of $l_{y,l}$ = 210 mm, the amplitude of the z-force rises significantly. At higher clamping distances the standard deviation also increases, especially at the length l_x = 80 mm, see Fig.9. As a result of the milling tests, it can be inferred that the workpiece quality is independent of the distance of the clamping points as well as that the forces are similar until the distance reaches a critical limit. If the distance is held lower than the critical limit the process remains stable. Thus cost reduction due to a reduction of necessary clamping devices for complex FRP workpieces are possible by utilization of the findings.

5. Conclusion and Outlook

Based on the results of the milling test following conclusions can be deducted:

- With increasing distance of the clamping lines the maximum forces during milling the edge increase strongly
- At low distances the forces can be correlated with the cutting steps
- The cutting forces in the x- and y-direction are unaffected by the clamping system and remain constant during all experiments
- The maximum z-force remains constant till the distance reaches a critical level of about $l_{y,l} = 210$ mm
- At a high clamping distance the process is getting unstable and a higher distribution of the measurements could be deducted.
- For milling the edge of CFRP workpieces with the used ply setup a clamping distance below $l_{y,l} = 210$ mm shows a high process reliability
- During all milling tests no influence of the clamping system and distance of the clamping points on the arising damage could be recorded.
- The support in z-direction is important for the design of a clamping system

In further experiments the behavior of the workpiece depending on different clamping situations will be analyzed. Emphasis was put on vibrations and the deflection of the workpiece as well as the resulting workpiece quality. Thereto, the clamping device will be modified to measure the deflection of the workpiece to compare the cutting force, deflection and workpiece quality. The main objective is the development of a mathematical approach to predict the behavior of the FRP workpiece during milling. These results will lead to a further improvement of the processability of FRP workpieces.

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